Power saving through state retention in IGZO-TFT AMOLED displays for wearable applications

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Abstract — We present a qHD (960 × 540 with three sub-pixels) top-emitting active-matrix organic light-emitting diode display with a 340-ppi resolution using a self-aligned IGZO thin-film transistor backplane on polyimide foil with a humidity barrier. The back plane process flow is based on a seven-layer photolithography process with a CD = 4 μm. We implement a 2T1C pixel engine and use a commercial source driver IC made for low-temperature polycrystalline silicon. By using an IGZO thin-film transistor and leveraging the extremely low off current, we can switch off the power to the source and gate driver while maintaining the image unchanged for several minutes. We demonstrate that, depending on the image content, low-refresh operation yields reduction in power consumption of up to 50% compared with normal (continuous) operation. We show that with the further increase in resolution, the power saving through state retention will be even more significant.

Keywords — *flexible displays, AMOLED, metal-oxide semiconductors, self-aligned TFT, state retention.*

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1 Introduction

Market research predicts[1] that by 2020, more than 70% of shipped smartphone displays will be active-matrix organic light-emitting diode (AMOLED) with flexible or curved AMOLED displays accounting for more than half of the overall smartphone and wearable display market. Resolution, mechanical flexibility, and power consumption are hereby the main drivers for further development of AMOLED displays. Especially for wearables like smart watches, power consumption is a decisive argument for the choice of display technology.

A popular approach to lower the power consumption are reflective liquid-crystal displays with memory-in-pixel. Depending on the light conditions and display content, a backlight can be switched on and the display runs with video refresh rate. Otherwise, if the content does not require constant refresh, the refresh rate can be slowed down or completely stopped while the image is retained although depending on the implementation with limited grey levels. In case of AMOLED technology, slowing down the frame rate or memory-in-pixel[2] are less obvious energy-saving strategies because the power required for light emission is generally dominant compared with the refreshing of the frame. This work attempts to quantify and measure the energy saving enabled by state retention based on the extremely low Ioff current of IGZO thin-film transistor (TFT)[3] in AMOLED displays.

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2 Display fabrication

Our TFT backplane[4] is based on self-aligned IGZO TFT. The choice of IGZO TFT allows a monolithic integration whereby the TFT is directly processed on a flexible thin-film moisture barrier.[5] Only at the end of the full process flow, the display is released from the temporary glass substrate by laser or mechanical delamination.

Using a self-aligned architecture allows to realize a TFT backplane with only four mask layers and reduced parasitic overlap capacitance (and therefore resistor–capacitor delay) compared with either etch-stop-layer or back-channel-etch architecture. This is especially beneficial for larger displays like 4k2k with higher frame rates and integrated line driver. The overall display integration scheme of frontplane and backplane is shown in Fig. 1.

On a temporary Gen1 (320 × 350 mm) glass carrier with a 16-μm thick solution coated polyimide film, a humidity and oxygen barrier[5] is deposited followed by a buffer layer to create an improved interface to the IGZO. Afterwards, IGZO (metal ratio = 1:1:1) is sputtered by direct current – physical vapor deposition followed by a wet-etch step to define the active semiconductor area. In a further step, we deposit 200 nm PECVD SiO_2 as a gate dielectric. Next, we deposit 100 nm Mo-alloy as a gate metal. The gate/dielectric stack is patterned within the same masking step. Subsequently, we deposit 200 nm PECVD SiN. The PECVD SiN fulfills the double purpose of intermetal dielectric and doping the IGZO in the areas not covered by the gate/dielectric stack with hydrogen. The contact opening for the source–drain contacts are opened up by dry etching. Mo-alloy with a thickness of 100 nm is deposited and patterned to define the source–drain contacts. The last step in the TFT process is a final anneal. Afterwards, we deposit and pattern an organic interlayer dielectric, metal anode, and an edge cover dielectric layer. The cross-section scanning electron microscopy of the full TFT backplane stack is shown in Fig. 2.

A photograph of the processed Gen1 plate is shown in Fig. 3.

This is followed by the deposition of an inverted orange small molecule organic light-emitting diode (OLED) stack (7 cd/A), a transparent cathode, and a transparent thin-film barrier. For the purpose of verifying our stack integrity, backplane functionality, and power consumption, we use monochrome small molecule OLEDs instead of full RGB,

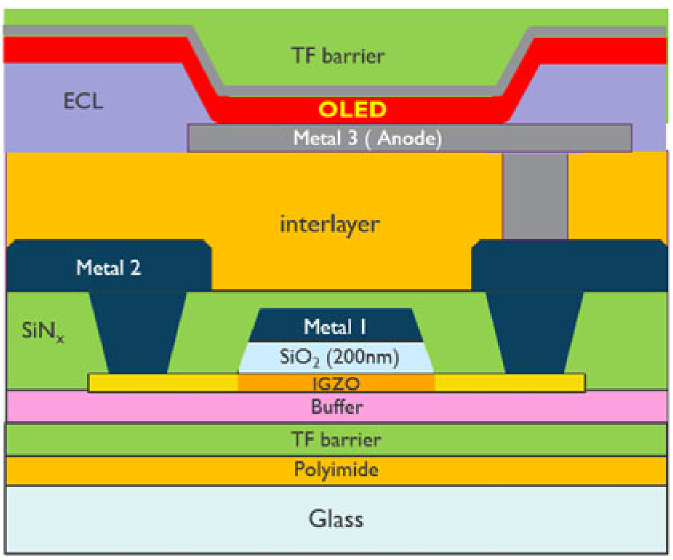

FIGURE 1 — Cross-sectional view of the seven mask backplane process of the active-matrix organic light-emitting diode display.

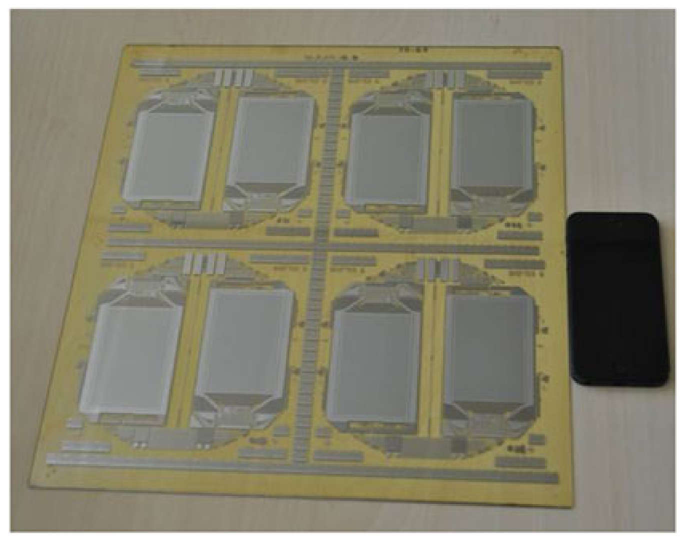

FIGURE 3 — Gen1 (320 mm × 350 mm) plate with thin-film transistor backplane on polyimide.

FIGURE 2 — Cross-section focused ion beam/scanning electron microscope image of the TFT backplane without organic light-emitting diode.

despite the three sub-pixel design of the backplane, which is fully compatible with an RGB frontplane process.

The design rules for all layers are fixed to a CD = 4 µm and an overlay <2 µm, compatible with an exposure using a large GenX scanner. We target a drive current of 0.5 µA @ V_{DS} = 8 V. A conventional 2T1C pixel scheme has been implemented, employing a drive TFT of W/L = 10.5 µm/7.5 µm and select TFT of W/L = 10 µm/4 µm. The longer channel length of the drive TFT improves the output resistance to >64 MΩ. The difference in output resistance between longer and shorter channels can be seen in Fig. 4.

For a channel length of 5 µm, we achieve a field effect mobility of ~11.5 cm^2/Vs. The transfer characteristics and a picture of the realized TFT is depicted in Fig. 5, and the TFT values summarized in Table 1. The long range Von uniformity across the full Gen1 plate is σ = 0.2 V for a 5 µm channel length and increases to σ = 0.4 V down to 3 µm channel length.

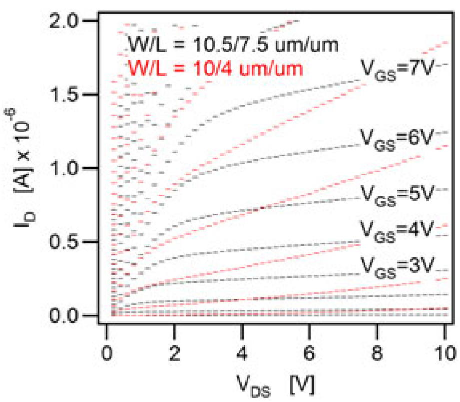

FIGURE 4 — Output characteristics of the drive thin-film transistor and the select thin-film transistor.

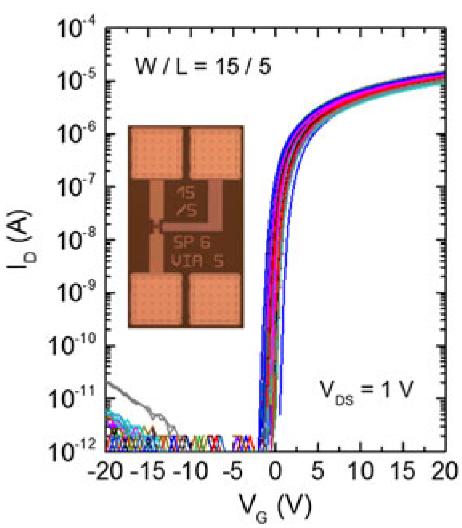

FIGURE 5 — Transfer characteristics of 75× self-aligned thin-film transistor with W/L = 15 µm/5 µm across a Gen1 plate (inset) thin-film transistor image.

TABLE 1 — Summary of thin-film transistor parameter.

W/L [µm/µm]	µFET [cm^2/Vs]	Von [V]	s^{-1} [dec/V]	Rout [MΩ]
10.5/7.5	11.3	−0.8	0.3	64
9/4	11.5	−1.1	0.3	33

The Ioff shown in Fig. 5 is in fact not the Ioff due to leakage but due to the limitations of the Gen1 measurement setup used for mapping. We therefore repeated the measurement of the off-current on a SUSS MicroTech PA300 probestation on a TFT with a large W/L = 200 µm/5 µm as shown in Fig. 6. The measured Ioff is significantly below <<1 fA/µm whereby the noise floor of the measurement setup is >50 fA, which is indicated with a dashed line.

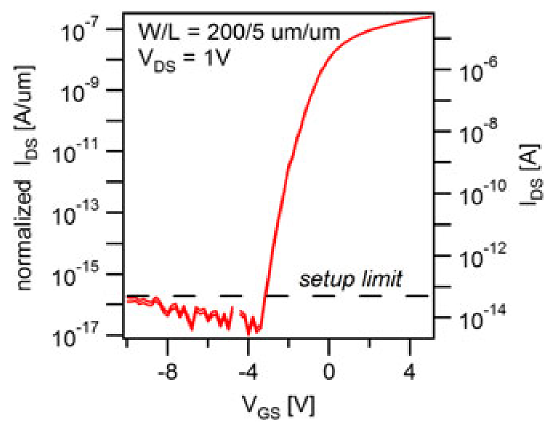

FIGURE 6 — Transfer characteristics of a thin-film transistor with large width using a PA 300 probe station.

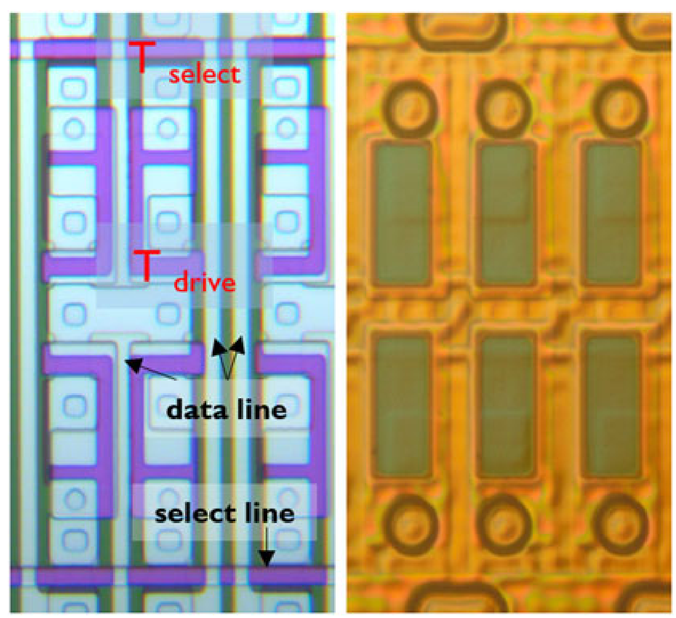

FIGURE 7 — Microscopic picture of the pixel (left) after thin-film transistor process; (right) after full display process.

A picture of the 340-ppi TFT backplane after the TFT process and after full display manufacturing can be seen in Fig. 7.

Finally, to drive the display, we bonded onto the PI substrate commercial COG gate driver IC with 480 channels and a LTPS source driver IC with 540 channels. An in-panel 3:1 MUX allows to switch between the three sub-pixels. The layout of the qHD (960 × 540 × 3 sub-pixel) display can be seen in Fig. 8 (left) and with an image applied in Fig. 8 (right).

At the end of the process flow, we release the AMOLED display by laser lift-off. The overall display is less than 60 µm thick and can be bent with a radius of 5 mm as shown in Fig. 9.

3 Display characterization

The overal specifications of the display are listed in Table 2.

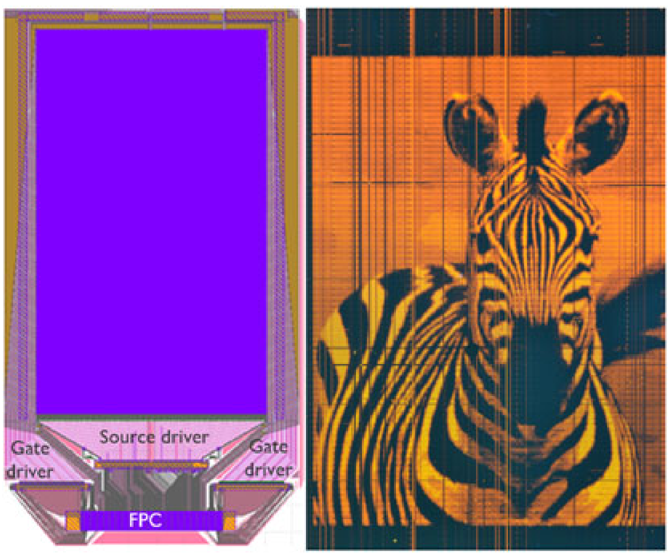

FIGURE 8 — qHD active-matrix organic light-emitting diode display (left) layout; (right) with applied image.

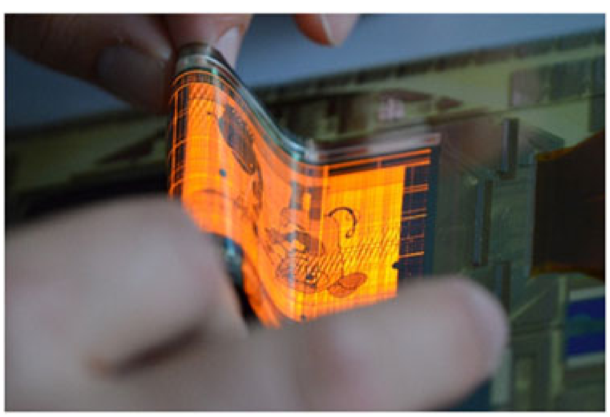

FIGURE 9 — Released flexible qHD active-matrix organic light-emitting diode display.

TABLE 2 — Display specification of this work.

Specification	Data
Panel size	3.2 in. (4.2 × 7.2 mm)
Pixel	qHD (960 × 540 × 3)
Resolution	340 ppi
RGB MUX	Yes
Date driver	LTPS driver IC
Bezel width	5 mm (no GIP)
Pixel engine	2T1C
Thin-film transistor	Self-aligned IGZO
Frame rate	60 Hz
Thickness	<60 um
Substrate	Polyimide

In the next step, we tested the state retention of the display by applying an image and switching off the power supply to the gate and source driver IC completely while maintaining the supply voltage at the OLED.

As can be seen in Fig. 10, the images are retained unchanged over more than 300 s. (Note: There are a several lines with line defects that are already visible at T = 0 s that are getting more pronounced at T = 300 s)

Subsequently, we measured the power consumption of the display. Hereby, we can measure seperately the current through the logic of both the gate and source driver, the current required by the select high and low and the current through the OLED.

Applying a uniform white image (fully on) with a frame rate of 30 fps, a brightness of ~100 cd/m^2, and a voltage across the OLED + drive TFT of 10 V, we measured a power consumption of approximately P_{OLED} ~ 460 mW. The power consumption of the source and gate driver IC was $P_{\mathrm{driver\_IC}}$ ~ 41 mW. Applying a white or black image changes the power consumption of the logic by only 1–2 mW. The power consumption of the select high and low remained below $P_{\mathrm{select}} < 1$ mW and is therefore nearly negligible. We have a select line capacitance of approximately 24 pF and a Vg,h = 10 V and Vg,l = −10 V. Changing the frame rate or the Vg,h and Vg,l will influence this P_{select} value by only factor 2 to 3. In the measured case, switching off the driver IC and relying on state retention, we can save for a fully-on image ~8% of the energy.

Depending on different usage scenarios and settings, the potential power saving can vary widely. The biggest effect stems from the target brightness and the actually shown content. If a newspaper article (black text on white background) is shown with a brightness of 500 cd/m^2 to be read in bright daylight, the power consumption of the driver IC becomes irrelevant. However, if we only present some basic information on a smart watch, for example, the time and status information during sleep mode, the possibility to completely switch off the display driver IC enabled by the low Ioff of the IGZO TFT becomes a significant energy saver.

In Table 3, we show estimates for diffrerent usage scenarios assuming a brightness of 100 cd/m^2 with an average efficiency of RGB OLED @ 10 cd/A.

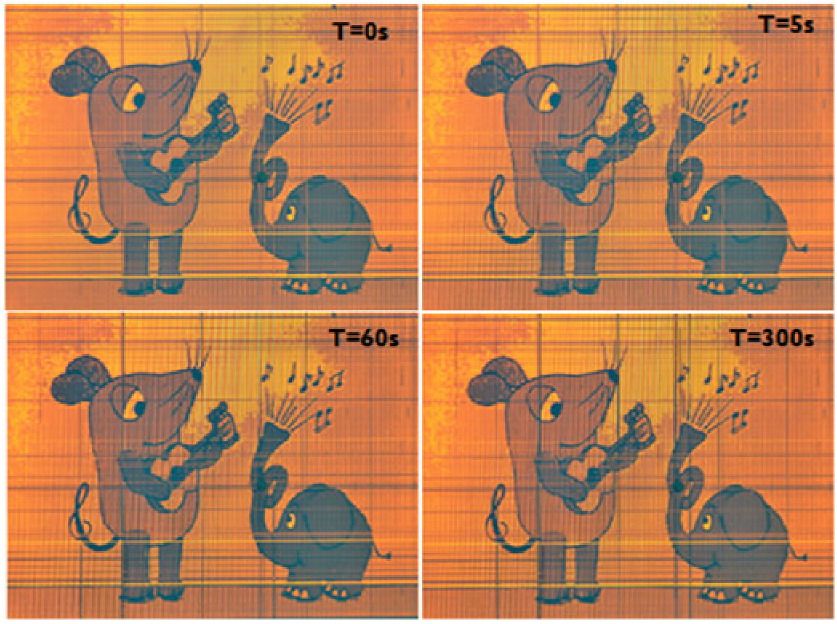

FIGURE 10 — Active-matrix organic light-emitting diode display with applied image during standard driving (T = 0 s) and 5, 60, and 300 s after the driver ICs have been switched off.

TABLE 3 — Estimated power saving for active-matrix organic light-emitting diode displays using IGZO thin-film transistor state retention.

Resolution [ppi]	Power [mW] OLED + drive TFT		Power [mW] IC	Power saving	
Size 3.2 in.	100% on	10% on	(line select + data driver)	100% on	10% on
340 @ qHD	300	30	40	12%	57%
680 @ FHD	300	30	80	21%	72%
1360 @ 4k2k	300	30	160	35%	84%

In a sleep information mode (10% of OLED pixels on), the energy saving can be more than 50%. If we increase the pixel density while maintaining the same size of the display, the potential energy saving increases further. The power consumption of the OLED remains constant with constant display area; however, the number of driver IC or the number of controlled I/O per IC increases. The time required to switch the driver IC on and refresh the frame is <30 ms. This means that, even if the applied image changes every second (e.g., analogue watch), implementing state retention can lead to energy savings.

4 Conclusion

A 340 ppi flexible AMOLED display with IGZO TFT has been shown. Utilizing the very low Ioff of IGZO TFT, we implemented state retention enabling us to completely switch off the driver IC for several hundred seconds while maintaining the image. We measured the resulting power saving and extrapolated those results for different usage scenarios.

Acknowledgment

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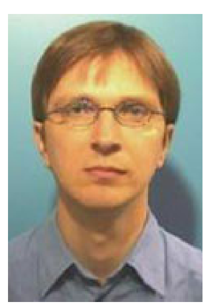


Soeren Steudel received his MSc degree in electrical Engineering from the Dresden University of Technology in Germany and a PhD degree from the Katholieke Universiteit Leuven, Belgium in 2002 and 2007, respectively. He is working since 2002 at IMEC on TFT's and rectifying diodes. This work resulted in more than 20 journal publications, several patents, and numerous conference contributions. His research interest includes the following: flexible backplanes for display application, process integration of organic and metal oxide semiconductor, and thin film circuits on foil. Currently, he is the team leader for organic and oxide electronic devices at IMEC.

Jan-Laurens P. J. van der Steen received his MSc and PhD degree in electrical engineering from the University of Twente, The Netherlands, in 2006 and 2011, respectively. Part of his PhD research was carried out at the University of Udine, Italy. Since 2011, he has been with Holst Centre, Eindhoven, the Netherlands. His research interests include device physics, with a focus on emerging technologies for flexible and stretchable electronics.

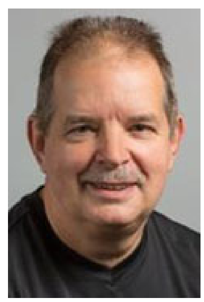
Manoj Nag received his Master of Technology degree in December, 1998 in Solid State Materials (SSM) from the Indian Institute of Technology, Delhi (IIT-Delhi), India. He worked as a Process Engineer with STMicroelectronics Singapore from January, 2000 to June, 2005. From July, 2005 to September, 2007, he was working as a Snr. Process Engineer with International Rectifier (Now Infineon) in UK. From October, 2007 to May, 2009, he worked as a Technology Transfer Module Leader with Qimonda Dresden, Germany. He is working as a Snr. Process Development Engineer in IMEC from June, 2009. He also received his PhD degree from Katholieke Universiteit Leuven (KUL), Belgium in December, 2016. His research interest includes a-IGZO TFTs for display backplanes and thin-film circuitry applications.

Tung Huei Ke was born in Hsinchu, Taiwan, on Janurary 20, 1981. He received his PhD degree at National Taiwan University in Taiwan in 2009 for the study in organic wide-gap semiconductors for the applications in organic light-emitting devices. He was a visiting scholar in TU Dresden in Germany in Prof. Karl Leo's group with a DAAD scholarship in 2007 and in Kyushu University in Japan in Prof. Chihaya Adachi's group for organic light-emitting transistors in 2008. Currently, he is working in the Large Area Electronics department at IMEC, Belgium. His main expertise relies in thin film CMOS technologies by organic and metal oxide semiconductors and flexible organic light-emitting devices for circuits and display applications.

Steve Smout was born in Leuven, Belgium, on March 17, 1984. He received his BSc degree in Chemistry in 2007 at the Katholieke Hogeschool of Leuven (KHLeuven), Belgium. Since then, he is working in the Large Area Electronics department at IMEC, Belgium. His main expertise relies in the research, development, and integration of organic and inorganic semiconductors for display applications and photo-lithography.

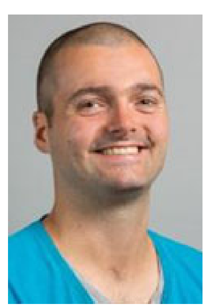
Thijs Bel is a process engineer in Holst Centre's GEN1 Flexible TFT Pilot Manufacturing Line. He has extensive process engineering knowledge dating back to the start of his tenure at Philips in Eindhoven in 1985. Initially, he worked on e-beam lithography, while in 1992, he transferred his attention to work on several new display projects within Philips. In 2007, he joined Philips Innovation Services, working on inkjet printing of OLED materials and encapsulation layers. Since 2015, he is working at Holst Centre/TNO and responsible for the realization of the backplane prototype for displays and imager sensors.

Karin van Diesen received her Bachelor of Applied Sciences degree in Organic Chemistry from Hogeschool Utrecht in 2006. Afterwards, she joined TNO at the department of Innovative Materials where she worked on self-healing materials and the development of nanoparticles for various applications. In 2009, she joined Holst Centre/TNO where she worked on the subject of foil bonding and debonding and the development of materials and processes hereof. From 2014 onwards, she joined the TFT Programme within Holst where she is currently responsible for the development of TFT processes and the integration of new materials in Holst Centre's GEN1 Flexible TFT Pilot Manufacturing Line.



Gerard de Haas is a process engineer in Holst Centre's GEN1 Flexible TFT Pilot Manufacturing Line. He has extensive experience in thin-film manufacturing processes dating back to his work as process operator at Biometrix, Eindhoven, in 1995. In time, he transferred his attention to troubleshooting manufacturing problems and, later, became an SEM analysis expert. In 2010, he joined Polymer Vision where he first started working on the flexible electronics. In 2012, he joined Holst Centre/TNO where he is currently responsible for the realization of flexible backplane prototypes.

Joris Maas received his BSc degree in Chemical Engineering in 1994 at the Hogeschool of Eindhoven, The Netherlands. He then joined the Philips CCD image sensors group in 1995 where he worked as a process engineer. In 2005, he joined Polymer Vision where has been working on organic and inorganic TFT process integration. In 2012, he joined Holst Centre/TNO were he continued his work on inorganic TFT processes and its applications in flexible electronics prototypes.



Joris de Riet graduated from Fontys Hogescholen, Eindhoven, in 2007 and afterwards joined Holst Centre as a process engineer. He has worked on encapsulation technology, nanoimprint lithography, and laser processes for the realization of flexible electronics. Recently, he joined the Holst Centre's TFT Programme where his current responsibilities entail the development of (laser) debonding processes as well as new TFT manufacturing processes in Holst Centre's GEN1 Flexible TFT Pilot Manufacturing Line.

Madelon Rovers received her Bachelor's degree in Chemical engineering from Fontys Hogescholen, Eindhoven, the Netherlands in 1998. After that, she started at Philips Electronics where she worked on the process development of LCD displays, plasma displays, and backplanes for X-ray detection. In 2011, she joined Holst Centre/TNO, where she initially worked on the development and implementation of process flows for creating innovative sensors and micro-power systems. Since 2013, she has been working on the development and integration of TFT processes for flexible electronics applications in Holst Centre's GEN1 Flexible TFT Pilot Manufacturing Line.

Roy Verbeek received his BSc degree in Chemical Engineering in 1995 at the Hogeschool of Eindhoven, the Netherlands. He then joined the Philips Research Inorganic Materials group in 1995 where he worked as a material/process engineer. In 2003, he joined Philips Innovation Services where he has been working on OLED displays, Molecular Diagnostics, and 3D switchable displays. From 2012 to 2015, he was team lead at the OLED service department of Philips Innovation Services. In 2015, he transferred to Holst Centre/TNO as the process engineer responsible for the development of flexible TFT technology in Holst Centre's GEN1 Flexible TFT Manufacturing Line.

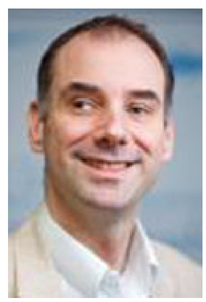
Marc Ameys was born in Aalst, Belgium, on March 9, 1983. He received his Master of Industrial Sciences degree in Electronics in 2006 from the Hogeschool Gent (HoGent), Belgium. From 2006 to 2011, he worked as a development engineer in the Media and Entertainment division of Barco. Specializing in analog, power supply, and led driving design for LED video walls. In 2011, he joined the Polymer and Molecular Electronics (PME) group of IMEC developing tools to analyze novel digital circuits and AMOLED displays.

Florian De Roose received his MS degrees in electrical engineering from KULeuven, Leuven, Belgium, in 2013. Afterwards, he joined the research team towards advanced thin-film applications at the Thin-Film Electronics group of *IMEC*. Concurrently, he is also part of the MICAS group of the KULeuven as a PhD researcher on advanced mixed-signal design in a-IGZO thin-film technology on flex. His research interests include display design, NFC, and sensor readout on flex and large area imaging, with special interest in system design of large area applications and the corresponding technology constraints.

Wim Dehaene has been a professor at KULeuven since 2002. Before that time, he was working for Alcatel Microelectronics as a senior project director. He holds a PhD (1996) and a master (1991) in electrical engineering from KULeuven. His main research interests are ultra-low power DSP and memories. Besides that, he also heads high-speed digital circuit research mainly in the domain of digital RF transmitters and digital AD convertors. Wim is also very active in the research towards novel STEM education programs for the Flemish secondary school system. He is a member of the ESSCIRC TPC and served on the ISSCC TPC for many years.

Jan Genoe was born in Leuven, Belgium, on May 19, 1965. He received his MS degree in electrical engineering and his PhD degree from the Katholieke Universiteit Leuven, in 1988 and 1994, respectively. Afterward, he joined the Grenoble High Magnetic Field Laboratory as a Human Capital and Mobility Fellow of the European Community. In 1997, he became a lecturer at the Katholieke Hogeschool Limburg (KHLim) in Diepenbeek, Belgium. Since 2003, he has been both professor at the KHLim and head of the Polymer and Molecular Electronics (PME) group of IMEC. His current research interests are organic and oxide transistors and circuits as well as organic photovoltaics. He is the author and coauthor of about 90 papers in refereed journals. Jan Genoe is a member of the IEEE.

Paul Heremans received his PhD degree in electrical engineering in 1990 at the University of Leuven, Belgium, on hot-carrier degradation of MOS transistors. He then joined the opto-electronics group of IMEC, where he worked on optical interchip interconnects, and on high-efficiency III-V thin-film surface-textured light-emitting diodes. His current research interest is oxide and organic electronics, including circuits, backplanes and memories, as well as organic photovoltaics. He is an IMEC Fellow, Director of IMEC's Large Area Electronics department and part-time professor at the Electrical Engineering Department of the University of Leuven.



Gerwin Gelinck received his PhD degree from the Technical University, Delft, the Netherlands, in 1998. He joined Philips Research as a Senior Scientist in 1998. From 2002 to 2006, he was the Chief Scientist of Polymer Vision. Since 2007, he has been a Program Manager/Director at Holst Centre. Since 2014, he is Professor at the Eindhoven University of Technology.

Auke Jisk Kronemeijer received his BSc degree in Chemistry (2004), MSc degree in Nanoscience (2006), and PhD degree in Applied Physics on the subject of Molecular and Organic Electronics (2011) all from the University of Groningen, the Netherlands. Afterwards, he joined the University of Cambridge, UK, as a Research Associate in Organic Electronics. After shaping the research agenda on the subject of *'Sensoring'* at KWR Watercycle Research Institute, he moved back into the development of organic and oxide TFT technology as a Senior Researcher at Holst Centre/TNO. In addition to his research activities, he currently manages Holst Centre's GEN1 Flexible TFT Pilot Manufacturing Line as well. The combined activities at Holst Centre/TNO are focused on the development of advanced TFT technologies and prototyping of flexible electronics applications such as flexible displays, imagers, circuitry, and sensors.